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The use of pipe elbows as flow meters.

Bakhteyar Husain
University of Tennessee

To the Graduate Council:

I am submitting herewith a thesis written by Bakhteyar Husain entitled "The use of pipe elbows as flow meters.." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Hydraulic Engineering.

Cecil S. Camp, Major Professor

We have read this thesis and recommend its acceptance:

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

August 1, 1948

To the Committee on Graduate Study:

I am submitting to you a thesis written by Bakhteyar Husain entitled "The Use of Pipe Elbows as Flow Meters." I recommend that it be accepted for nine quarter hours credit in partial fulfillment of the requirements for the degree of Master of Science, with a major in Hydraulic Engineering.

Major Professor

We have read this thesis
and recommend its acceptance:

Harry H. Ambrose

Julian R. Fleming

Accepted for the Committee

E. A. Waters

Dean of the Graduate School

THE USE OF PIPE ELBOWS AS FLOW METERS

A THESIS

Submitted to
The Committee on Graduate Study
of
The University of Tennessee
in
Partial Fulfillment of the Requirements
for the degree of
Master of Science

by

Bakhteyar Husain

ACKNOWLEDGEMENTS

This work was done in the Hydraulics Section of the Civil Engineering Department of the University of Tennessee. Prof. Cecil S. Camp sponsored the study as Major Professor and Head of the Section. We gratefully acknowledge all his active help and directive guidance in this work.

Professors Julian R. Fleming and Harry H. Ambrose have also been helpful in various ways, and we are thankful to them for this.

PURPOSE

All the previous studies of pipe elbows for use as flow meters have led to the conclusion that it is necessary to calibrate each elbow desired to be used as an accurate flow meter in its service location. Considering the various advantages an elbow meter possessed over the other types, this limitation looked like an unfair handicap to it.

This study was undertaken to investigate the possibilities of using an elbow meter without its calibration being necessary in the service location. In this connection more attention was devoted to the practical details of the problem than to its theoretical aspects. References to literature, dealing with the problem on a purely mathematical basis have, however, been given where necessary.

Due to limitations of time and material, it was not possible to make a very exhaustive study of the problem. Only seven elbows of 2-1/2-inch nominal diameter were studied for this work, and it is realized that the generalization of these results may, in some ways, be rather unwarranted.

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INTRODUCTION

It was known for a long time that when water flows around a bend it exerts greater pressure on the outer side than on the inner side of the curved section and that the difference of pressure between the two sides increases with the velocity of flow. Attempts to establish precise relations between these two variables, the difference of head and the velocity of flow, were, however, not made until quite recently. Probably the loss of head at pipe bends was a headache diverting the attention of all hydraulicians from this comparatively harmless phenomenon.

The idea of using pipe elbows as flow meters by relating the discharge in pipe to the differential head seems to have been first presented in a practical form by Jacobs and Sooy in 1911.[1] Then after a long period of neglect, it was again picked up by W. M. Lansford in 1934[2] and continued with some progress until the beginning of World War II.

The use of pipe elbows as flow meters, or in other words, the use of elbow meters, has a distinct advantage over the other types of flow meters. The elbow is a very common fixture in most pipe lines, hence an elbow meter would not necessarily need extra space and structures

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1. Gaskell S. Jacobs and Francis H. Sooy, "New Method of Water Measurement by Use of Elbows in a Pipe Line," Journal of Electricity, Power, and Gas, vol. XXVII, July 22, 1911.

2. W. M. Lansford, "Use of an Elbow in Pipe Lines as a Means of Measuring the Flow of Water," Bulletin of Associated State Engineering Societies, vol. IX, No. 2, April 1934.

to install it. The initial cost and maintenance of these is very low compared to other types of meters. From a hydraulic point of view an elbow would cause the same loss of head whether it serves as a meter or not. The differential head produced is quite large, and functionally an elbow meter is a flow meter.

A great handicap in the use of commercial elbows for precision metering is the difficulty of calibrating each elbow in its service location. Probably the erratic behavior of these meters is due to the irregularities in the shape, size, finish, and joints of the commercial elbows. There is no theoretical reason why a carefully manufactured elbow would not give the same degree of accuracy as other dynamic-head meters do. If after proper investigation, standard proportions and other requirements for the various sizes of elbows are determined, it may give us another type of good flow meter. In the meantime, commercial elbows offer a cheap and handy type of meter, which will give flow measurements within about 10 percent error without much trouble.

THE METER

Its Parts and the Factors Involved

According to the A.S.M.E. classification, the elbow meter is a centrifugal (kinetic) head type of rate-meter.[3] The primary element consists of a pipe elbow with pressure holes on its concave and convex sides. When water flows through the elbow, the change of direction of flow, hence that of momentum, develops a differential pressure between the two sides of the elbow. The difference in pressures on the two sides can be observed on two separate gauges, or on a single differential pressure gauge. The rate of flow, or the average velocity of flow in pipe, can then be inferred from this differential pressure, theoretically, on the principle of centrifugal change of velocity pressures across a curved stream, or practically, from empirically determined relations between the two variables.

Lansford made an analysis of flow around bends in which he assumed that the entrance velocities are all equal, that no loss of energy occurs, and that the stream lines and the center line of the bend are concentric. He obtains the relationship:[4]

$$h = C \frac{V^2}{2g} = \frac{(R - r)^2}{\left(\log \frac{R}{r}\right)^2} \left(\frac{1}{r^2} - \frac{1}{R^2}\right) \cdot \frac{V^2}{2g} \qquad (1)$$

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3. "Fluid Meters, Their Theory and Application," part I, fourth edition (New York: American Society of Mechanical Engineers, 1937), p. 41.

4. W. M. Lansford, "The Use of an Elbow in a Pipe Line for Determining the Rate of Flow in the Pipe," Bulletin No. 289 (Urbana: University of Illinois Engineering Experiment Station), p. 21.

where,

h = difference of pressure between inside and outside curves of the elbow, in feet of water.

C = constant for an elbow = $\frac{(R-r)^2}{\left(\log \frac{R}{r}\right)^2}\left(\frac{1}{r^2}-\frac{1}{R^2}\right)$

V = average velocity in feet per second (across a diametrical element).

R, r = radii of curvature of the outside and inside curves of the elbow in feet.

and g = acceleration due to gravity, in feet per second.

This equation can also be written in the form,

$V = \frac{1}{C} \cdot \sqrt{2gh}$, or if "a" is the cross-sectional area of the elbow in square feet:

$$Va = \frac{a}{C} \cdot \sqrt{2gh} \qquad (2)$$

$$\text{or,} \quad Q = C' \sqrt{h}$$

where,

$Q = Va$ = discharge through the elbow, c.f.s.,

and C' = another constant = $\frac{a}{C}\sqrt{2g}$

In another analysis on the basis of Newton's second law of motion, he derives the equation:[5]

$$h = \frac{2D}{r} \cdot \frac{V^2}{2g} \qquad (3)$$

where, D = diameter of elbow in feet.

and, r = radius of the mass center of the water flowing in bend in feet.

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5. *Ibid.*, p. 23.

Addison,[6] with a similar assumption, that a pure free vortex flow exists around a pipe bend, obtained the relation:

$$q = \sqrt{2gh} \cdot \frac{R^2 - C^2}{\sqrt{RC}} \cdot \pi\left[R - \sqrt{R^2 - C^2}\right] \tag{4}$$

where:

q = discharge,

h = differential head,

r = radius of elbow curve at the center line,

c = inside radius of elbow,

and g = acceleration due to gravity.

All in consistent units.

In the above equations q is proportional to $\sqrt{h}$ or

$q = C_k \sqrt{h}$, where C_k is a constant.

The actual differential head and discharge, however, do not usually abide by these analytical relations when ordinary elbows are used, and it becomes necessary to introduce an empirical factor to take care of any differences. Sometimes this is done by using a relation:

$$Q = k\, q \tag{5}$$

in which Q = actual discharge through elbow,

and k = a constant of proportionality, determined by the calibration of elbow.

It is assumed in this case that the theoretical and actual discharges bear the same constant relation to each other for all rates of flow. In case the actual discharge is proportional to some other

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6. Herbert Addison, "The Use of Pipe Bends as Flow Meters," Engineering CXLV, p. 227, March 4, 1938.

exponential power of "h" than 1/2, it would be better to express the relation in some other form.

Lansford found that for the equation, $h = KV^n$, the value of the exponent of velocity, n, is different for flanged and threaded elbows. The value of "n" are approximately 1.93 for flanged elbows and 2.00 for the threaded elbows.[7] Jacobs and Sooy found a value of 1.9 for "n". It appears more logical to take the variables for calibrating a flow meter as the differential head and discharge, rather than the differential head and velocity.

Hence, we adopt the general form of equation as:

$$Q = C\,H^n \tag{6}$$

where, Q = rate of flow in cubic feet per second,

C = empirically determined constant,

H = differential head in feet of water,

n = exponent of H, slope of the line in a logarithmic plot of Q vs. H; to be found empirically.

The factors that seem to affect the working of an elbow when used as a meter are its diameter, radius of curvature, location of the elbow in the pipe line, type of joint with the pipe, location and type of pressure connections, and the material and finish of the inside of elbow.

Diameter of elbow. The actual diameter of the elbow determines the velocity of water particles around the curve which produces the differential head. The diameter may also be a factor in determining the flow pattern that is established within an elbow.

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7. Lansford, *op. cit.*, p. 18.

In the case of flanged elbows, the inside diameter of the pipe and the elbow is the same, while with threaded elbows, there is a slight enlargement of the flow area through the elbow. This causes a decrease in the average velocity through the elbow and produces some extra disturbances at the joints. The possibility of using an elbow of smaller diameter than the pipe, with a reducer and an enlarger on the two sides, has been suggested to get increased pressures in the elbow.[8] But this arrangement combines a venturi and an elbow meter and should give the advantages as well as the disadvantages of both.

Radius of curvature. The radius of curvature of the elbow determines the circular motion of the liquid around the bend and is, therefore, the second most important factor affecting the working of an elbow.

It is obvious that conditions of a free vortex do not occur in the whole length of an ordinary elbow. Figure 1 illustrates the point. In a sharp turn as in figure 1a, the streamlines form a vena-contracta downstream from the inter-section,[9] and cannot take the curve along concentric paths. The radius of curvature of stream lines is changing throughout, great turbulence is caused below the vena-contracta, and for the same deviation such a joint would cause a maximum of energy loss.

Figure 1b shows a bend in which perfect conditions of a free vortex occur. The stream lines are concentric with the elbow and no turbulence

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8. *Ibid.*, p. 11.

9. A. H. Gibson, *Hydraulics and Its Applications* (London: Constable & Co., Ltd.), p. 251.

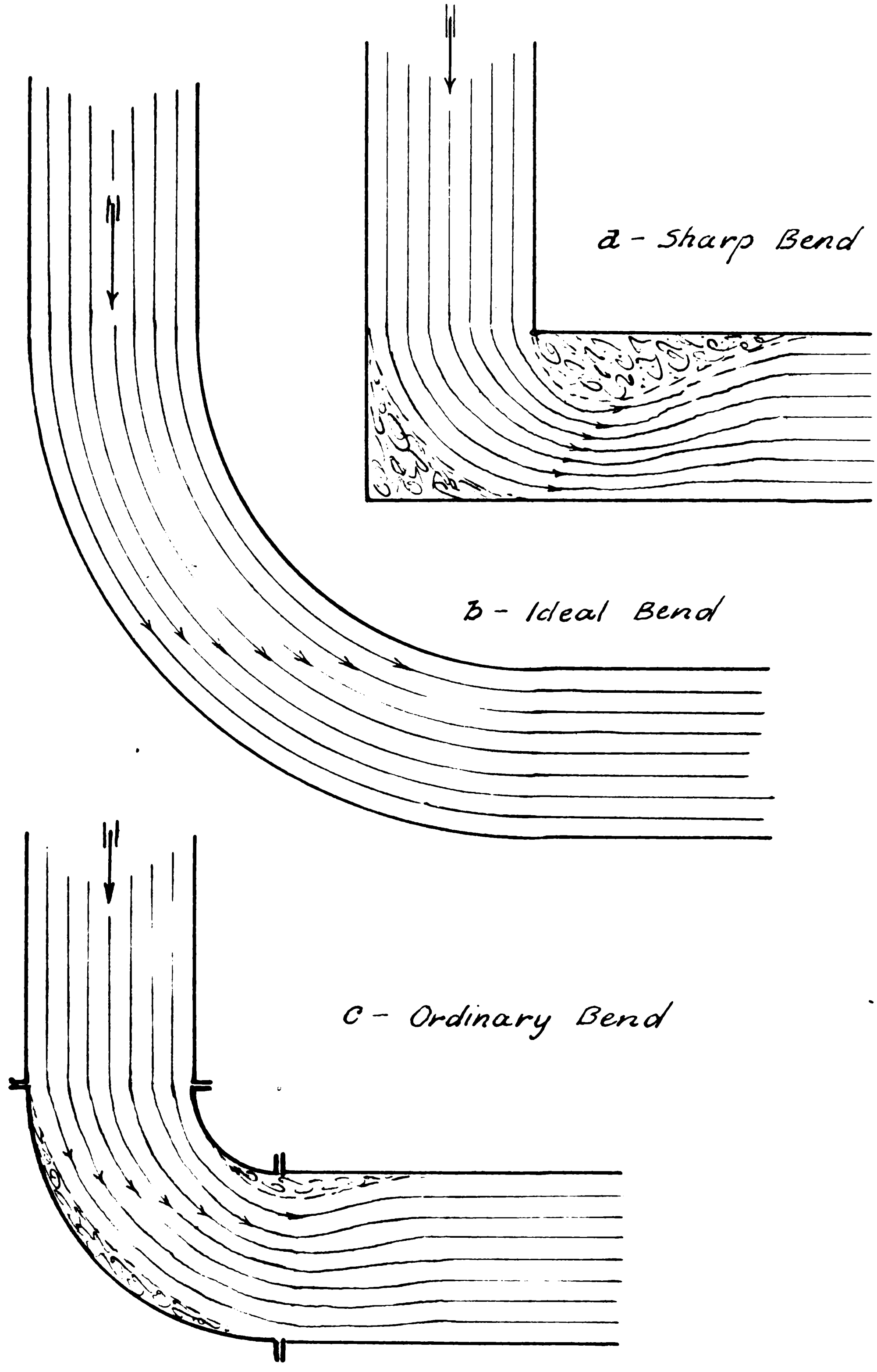

FIGURE 1

is caused downstream. The velocities are greatest at the inside and least on the outside of the bend. It has been suggested that approximately such conditions prevail when the relative radius $\frac{R}{d}$, (which is a ratio between the bend radius, R, and the pipe diameter, d) is in the neighborhood of 3 or 4.[10] It is then, in such a bend, that the values of "C" and "n" will be very nearly the same as those found on an analytical basis.

However, since these proportions and probably other conditions of the experiments in which those results were obtained, do not exist in the case of common commercial elbows, we shall assume that some combination of the two conditions, such as the one illustrated in figure 1c, exists in an ordinary elbow. The effect of the change of radius of curvature becomes thus uncertain; except for the fact that with increasing radius, the difference of pressure on the two sides will become smaller.

Location of elbow in the pipe line. The position of an elbow relative to the other fixtures in the line has much to do with the flow regime through the elbow. A long length of straight pipe preceding an elbow will give a fairly uniform and symmetrical distribution of velocities at the approach to the elbow. A valve, tee, elbow, or some other fixture, if present within a short distance upstream from the elbow causes the distribution of velocities and pressures to be so disturbed as to be practically unpredictable.

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10. K. Hilding Beij, "Pressure Losses for Fluid Flow in 90° Pipe Bends," United States Bureau of Standards, Journal of Research, XXI:10, No. 1 (RP 1110), July 1938.

What pipe length should precede an elbow meter to insure satisfactory performance would depend on the nature of the disturbing element upstream, diameter of the pipe, and the highest velocity of water in the pipe. Lansford found that twenty-five diameters of straight pipe preceding an elbow would be satisfactory.[11] Hoffman could detect disturbances up to fifty diameters below the bend in his smooth brass piping.[12]

Addison found, however, that even when he placed the elbow meter immediately following another elbow, it operated satisfactorily. In both the continuous and reversed curvature positions, the points obtained for the graph were quite consistent; the only difference was in the value of the constants.[13] Hence, it seems that if the elbow meter can be calibrated in place, it can be located anywhere in the line. But if an uncalibrated elbow is to be used, or if it is desired to use the same elbow in different setups, it is better to eliminate this factor by allowing a reasonable length of straight pipe to precede it.

Location and type of pressure connections. All through an elbow there is a difference of pressure between radial points on the inside and outside of the curve. Hence, any two points can be chosen to locate the pressure holes. Usually these are placed at 45 degrees in the plane of symmetry of the elbow. These points are easy to locate and convenient for connecting pressure taps.

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11. Lansford, *op. cit.*, p. 32.

12. A. Hoffman, "New Investigations to Determine the Pressure Loss in Pipe Bends," Hydraulic Laboratory Practice (New York: A.S.M.E., 1929), p. 473.

13. Addison, *op. cit.*, pp. 228-229.

Figure 2[14] will show that a maximum of pressure difference between the inside and outside of an elbow occurs at about 22-1/2° from the upstream tangent. For measuring differential head at low velocities, this may be a more favorable place.

In a particular setup, Lansford tried three locations of the pressure taps, at 45 degrees from each flange, near the exit flange of the elbow, and near the entrance flange; the last location proved most satisfactory in giving least pulsation of the gauge columns.[15]

Smaller holes at the pressure taps are desirable for keeping the pulsation of gauge columns low, but have the disadvantage of being liable to be choked up easily.

Type of joint with pipe. The best joint for a metering elbow is one giving a smooth surface at both the joints. Regular streamlines through the elbow create steady pressure differences in the elbow, and the velocity pressure relations are also regular. Welded, flanged, or Victaulic (see plate VI) joints would be better than threaded ones in this respect. It seems, however, that if the square ends of a threaded pipe were bevelled out from the inside, it would help some in keeping the streamlines by the sides of the elbow.

Roughness of the elbow. This is comparatively an unimportant factor, but its isolated effect on two otherwise identical elbows is not, so far, definitely known. Addison[16] reports on inconclusive evidence, that

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14. David L. Yarnell, "Flow of Water Through 6-Inch Pipe Bends," Technical Bulletin No. 577 (Washington: United States Department of Agriculture, October 1937), pp. 23 and 25.

15. Lansford, op. cit, p. 12.

16. Addison, op. cit., p. 228.

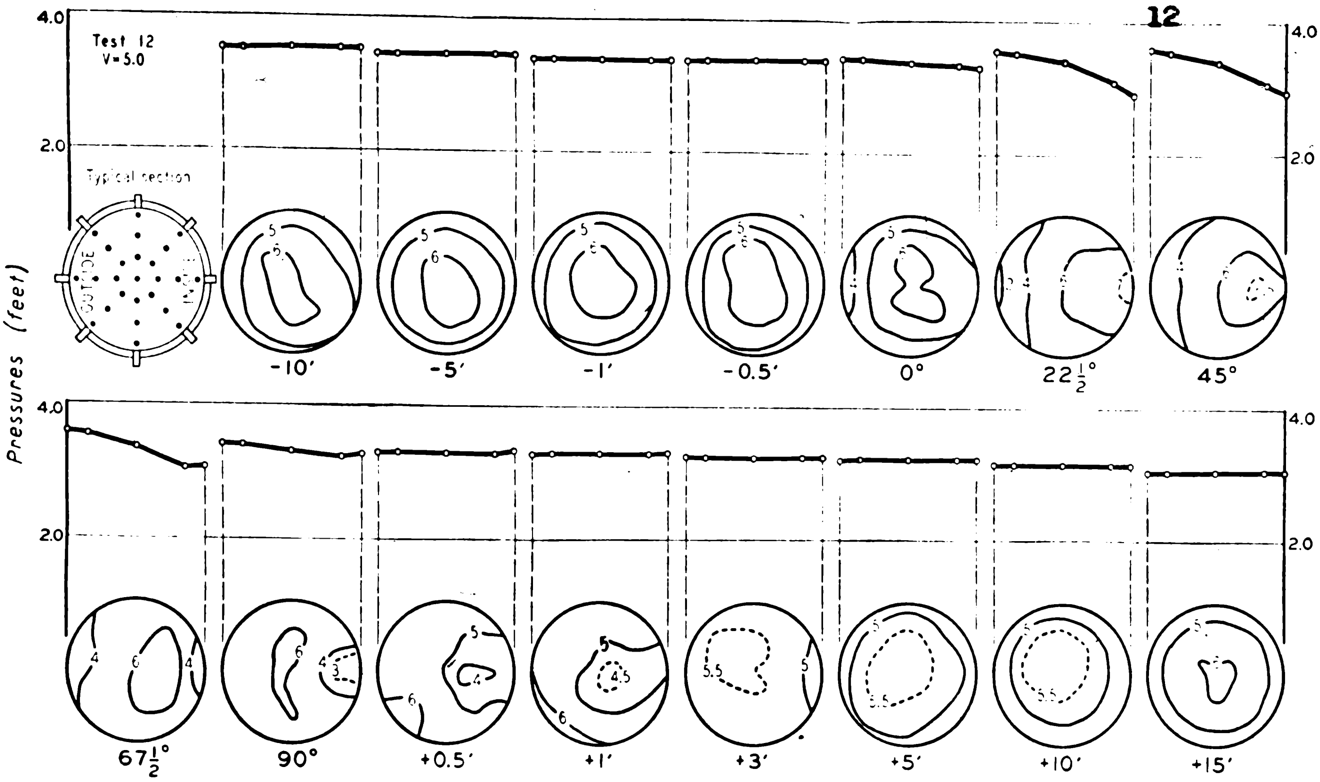

FIGURE 8. Velocity distribution and peripheral pressures in standard bend with approximately uniform velocity distribution in approach tangent; mean velocity, 5 feet per second.

Figure 2 - Velocity and Pressure Distribution in a Pipe Elbow.

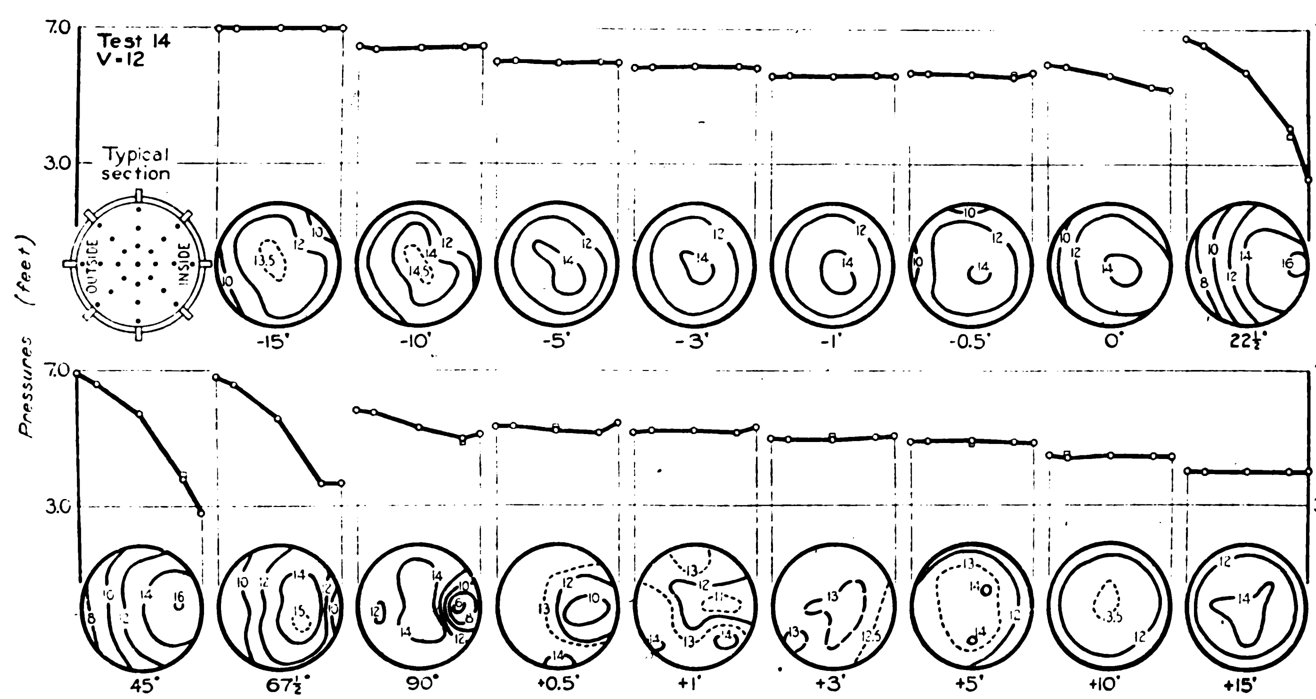

FIGURE 10. Velocity distribution and peripheral pressures in standard bend with approximately uniform velocity distribution in approach tangent; mean velocity, 12 feet per second.

the material and finish of the pipe walls, other things being equal, have little effect on the value of the coefficient of discharge, k (page 5).

Roughness of a ferrous pipe may vary due to rusting. The worst effect of rusting, however, appeared at the piezometer holes. Here, ridges of rust are built up around the holes in such a way as to falsify the pressure indications.[17]

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17. Beij, *op. cit.*, p. 15.

APPARATUS

Seven commercial types of 90° elbows of 2-1/2-inch nominal diameter were tested. These were numbered consecutively from 1 to 7 as detailed below.

Elbow number	Description
1 and 2	Standard short radius, R = d; galvanized; threaded; actual inside diameter 2-7/8 inches.
3 and 4	Standard short radius, R = d; with slightly longer threading space than 1 and 2; threaded; cast iron; actual inside diameter 2-7/8 inches.
5 and 6	Standard short radius, R = d; threaded; cast iron; actual inside diameter 2-7/8 inches. Different make than numbers 1 and 2.
7	Short radius, R = d; thinner metal than other elbows; Victaulic joints; cast iron, actual inside diameter 2-1/2 inches.

The elbows listed together are of the same make, and it was attempted to see that they were of similar shape and free of irregularities. Ordinary galvanized pipe was used for all work. Two, 2-1/2-foot lengths of the pipe were especially turned on a lathe to make connections for the Victaulic elbow (see plate VI, page 19).

The elbows were converted into meters by connecting pressure taps, at 45° from each flange, and in the plane of symmetry of the elbow on its concave and convex sides. Three ways of attaching the nipple to the elbow were adopted.

On elbows 1, 3, and 7 (see plates IV and VI) the 1/8-inch standard nipple was first welded on the elbow at the correct location and

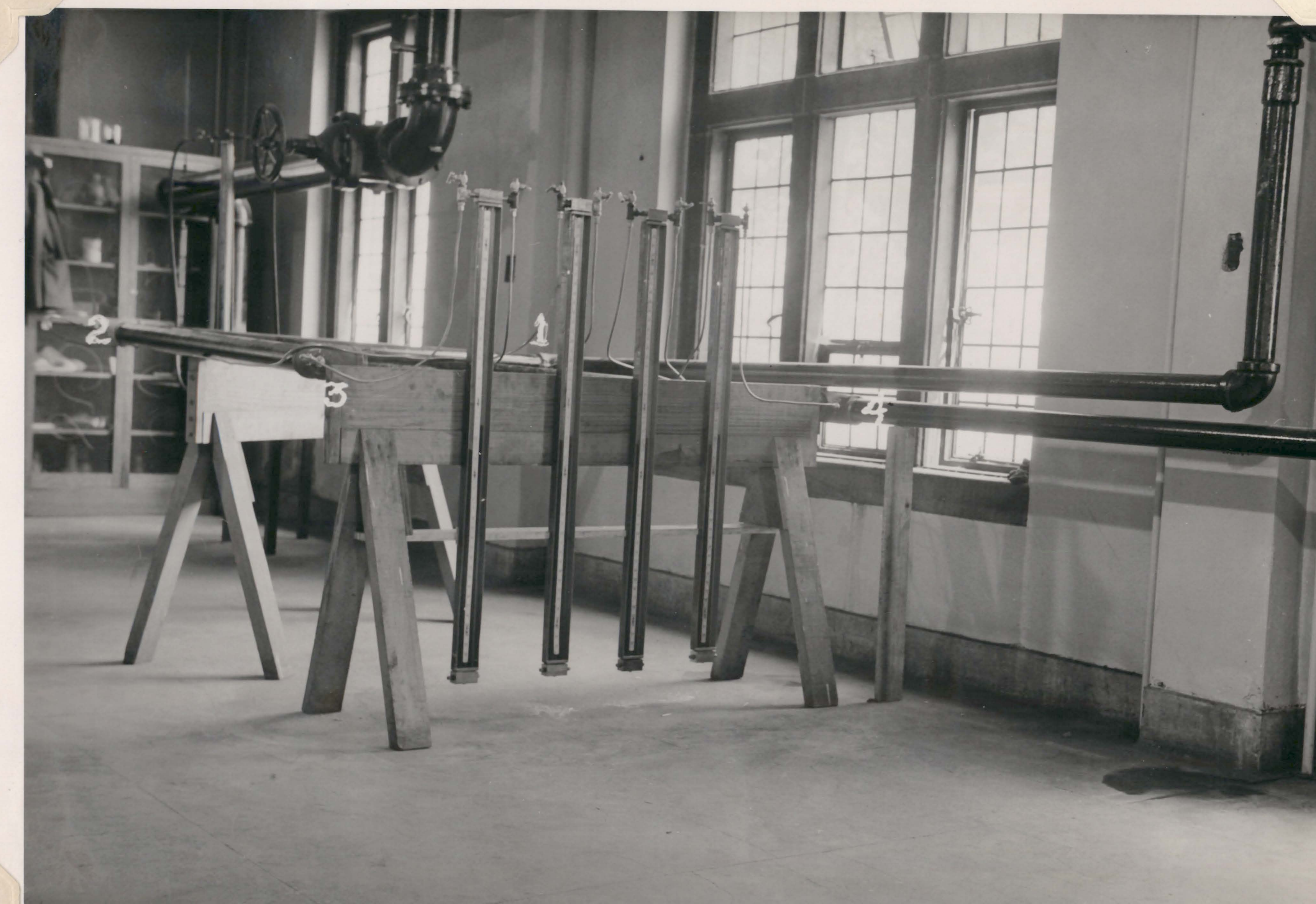


Plate I - Set-up for Testing Four Elbows at a Time

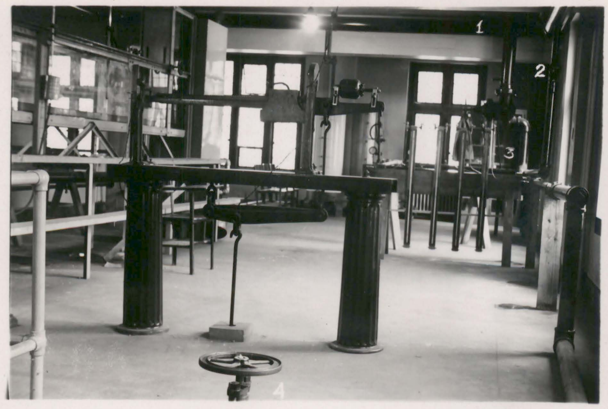


Plate II a - General View of the Apparatus. 1. Supply main; 2. Upstream supply valve; 3. Test elbows and manometers; 4. Downstream control valve.

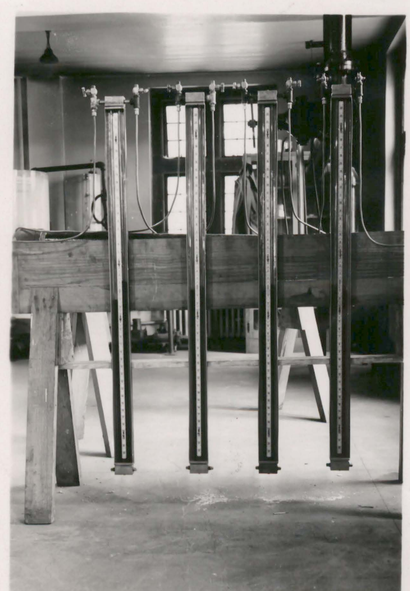


Plate II b - Set of Four Manometers Used in the Tests.

Plate III - Pressure Connections
on Elbow No. 2.

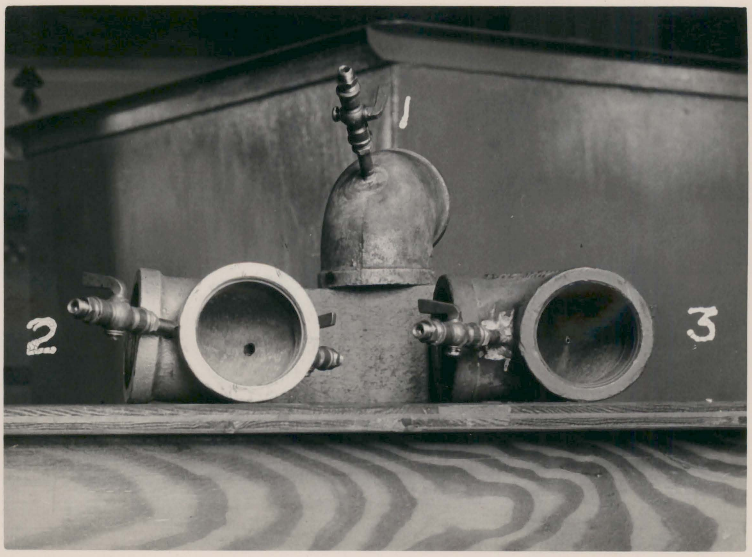


Plate IV a - Difference Between a Tapped and a Welded Pressure Connection.

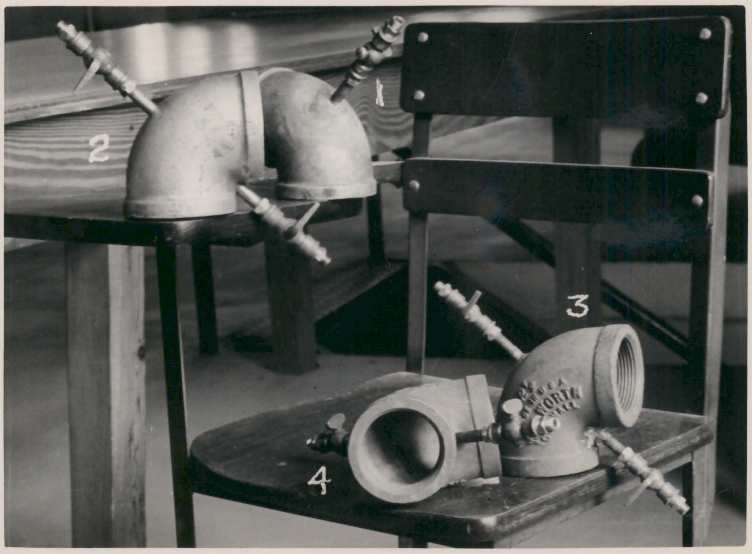


Plate IV b - Elbows Nos. 1 and 2 (galvanized), 3 and 4 (cast iron).

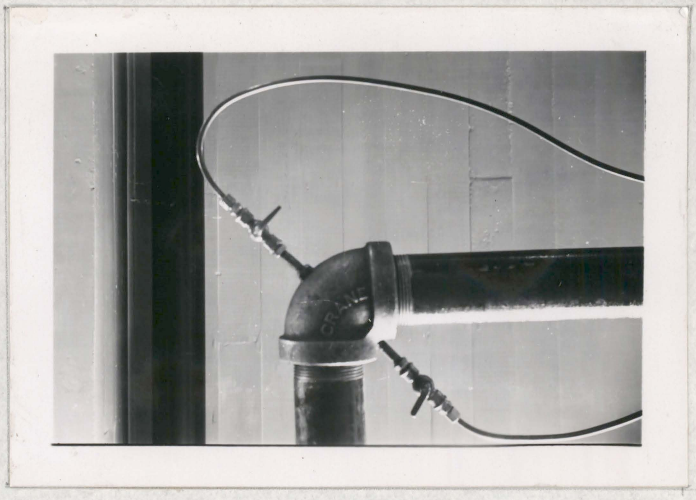


Plate V a - Elbow No. 5 in Position. The Outer Pressure Connection was Tapped into Knob.

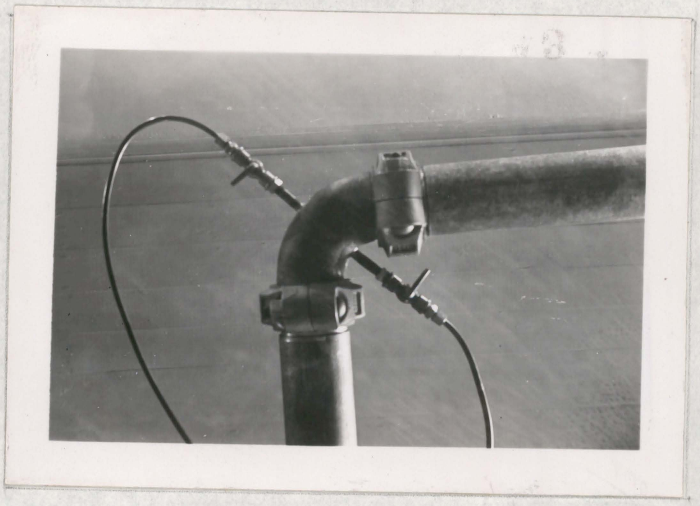
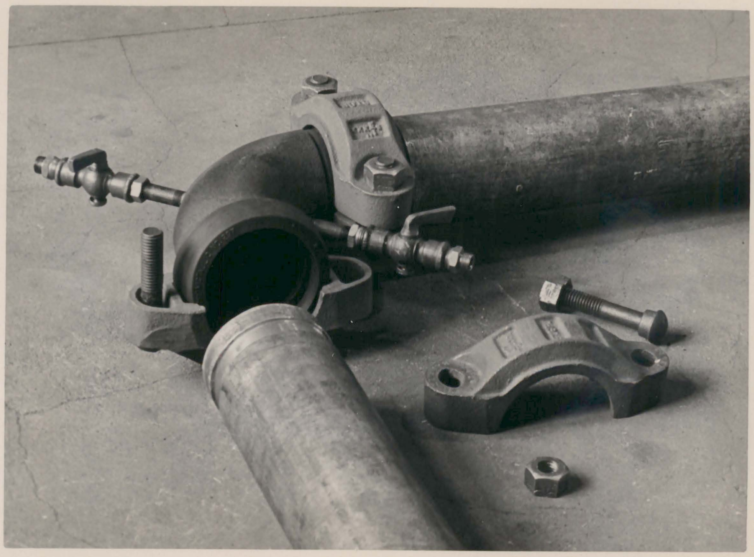


Plate V b - Victaulic Elbow in Position. (No. 7)



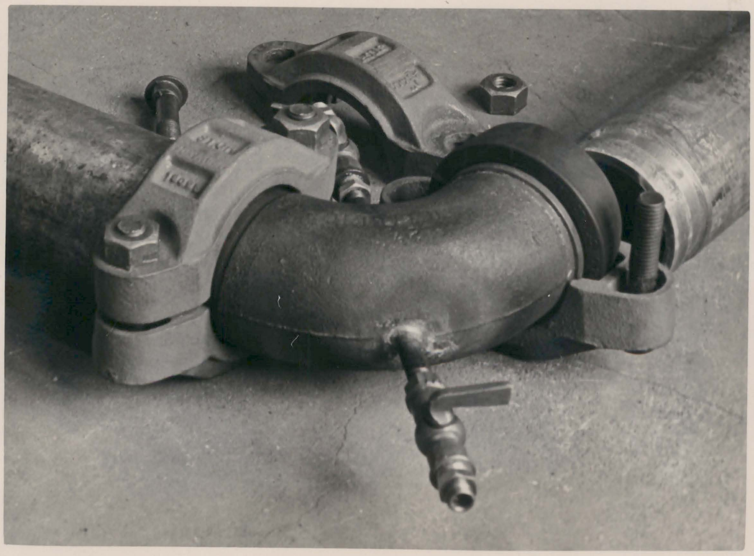


Plate VI a & b - Victaulic Pipe-and-elbow Connection then a 1/8-inch hole was drilled through the nipple into the elbow. Drill burrs on the inside were smoothed off. This procedure is suitable for elbows with a thin shell, where there is only a small thickness of metal to hold threads. In galvanized elbows, however, the heat of welding burns off the zinc, and it is advisable not to use brass nipples which become quite brittle after being heated once.

On elbows 2, 4, and 5, a 3/16-inch hole was first used at the required position of the pressure tap, then the hole was tapped, and the nipple was screwed into it. Care was taken to see that the nipple did not project into the elbow (see plates III and IV). In elbows which provide an ample thickness of metal at the correct place, this is a convenient and structurally strong pressure connection. There is, however, no control on the size of the hole to be made into the elbow, which has to be as big as the outer diameter of the nipple.

In the third type of connection, on elbow No. 5, advantage was taken of the presence of a knob on the outer side of the elbow (plate Va). The first 3/16-inch hole for tapping was not carried into the elbow, but stopped about 1/4-inch short of it. Then a smaller hole of 1/8-inch size was drilled in through the rest of the metal to provide the pressure holes. This arrangement requires about 3/4-inch thickness of the metal on both sides, which, in this elbow, was provided by the joined elbow collars on the inside, and the small square casting knob on the outside.

The connections between elbows and manometers were of 1/8-inch copper tubing with beaded ferrule connections. Over the nipple on the elbow was fitted a 1/4 - 1/8 inch reducing bushing, then a 1/4 inch stop cock, and then the tubing connection (see plates III and V). The stop cock is useful for disconnecting the elbow from the manometer.

The manometers (plate IIb) were of the straight tube type, with a reading length of 3-3/4 feet. These were prepared in the laboratory, with channel iron supports and stainless steel top and bottom blocks. Air cocks were provided in the top blocks to let all air out of the tubing before taking pressure readings. As already stated, the maximum range of these was about 45 inches, while the readings could be approximated to within one-five-hundredths of a foot quite easily. The liquid used was acetylene tetrabromide of specific gravity 2.95 (commercial name, "Merriam Liquid Number 3").

A general view of the apparatus is shown in plate IIa. Water was pumped by a motor driven centrifugal pump, against an air-cushion in a surge tank, into the 6-inch pipe main (marked 1, on plate IIa). The maximum discharge available was about one cubic foot per second. From the main, water flowed into a 4-foot vertical pipe, which had the upstream control valve (marked 2) for the setup under test. The vertical pipe was connected, through a 90° elbow, to a straight horizontal pipe, 10-1/2 feet in length. This pipe (10-1/2 ft. = 50 d) preceded the first elbow under test (marked 1 in plate I), whose position was designated as "A" for reference.

The elbow at "A" was followed by 5 feet of straight pipe, which had the second elbow at its other end, in position called "B" (2, in plate I). Downstream from "B" there was again 5 feet (24 d) of pipe leading to the position "C", which was again followed by a 5-foot length of pipe. Thus, the last elbow (marked 4 on plate I), which was in position "D", closed a square and was located under the first 10-1/2 foot horizontal pipe. Position "D" was followed by 8 feet of pipe down stream.

The following gives a tabular statement of the positions of the elbows:

Position	Length of Straight Pipe in Feet	
	Upstream	Downstream
A	10-1/2 (50d)	5 (24d)
B	5 (24d)	5 "
C	5 "	5 "
D	5 "	8 (38d)

Figures in parenthesis indicate the length of pipe in terms of pipe diameters.

Below the 8 feet length of pipe following the elbow in position D, the size of pipe was enlarged to 3 inches and a Victaulic joint coupling was provided to facilitate the dismantling of upstream apparatus. The 3-inch pipe led through a downstream control valve (4 on plate IIa) into the weighing tank.

The weighing tank was of 30,000 pounds maximum capacity, and sensitive to about 5 pounds.

<u>Test procedure</u>. During the tests, the upstream valve was kept fully open while discharge was controlled with the downstream valve. A stop watch, giving time in seconds, was used for recording time. The duration of time for a run of constant discharge was usually determined by the time required to read all the manometers under observation. The general sequence of steps for taking a set of readings was as follows:

1. Discharge varied with the downstream valve;

2. Stop watch started for the scale beam balancing at some convenient weight;

3. Weight increased on the scale beam by the required amount; and

4. Watch stopped for a second balancing of beam.

For all the elbows, differential pressure and discharge readings were taken for a good range of average velocities in pipe--from about one foot per second to above 15 feet per second. In plotting the results on logarithmic coordinates, the points at velocities lower than about two feet per second, sometimes deviate from the general curve probably due to the reduced sensitivity of the manometers and the weighing tank.

RESULTS

With the data collected curves were plotted on logarithmic coordinates, to find pressure-discharge relations for all elbows in the form of equation 6 on page 6. In figure 2A there have been plotted points for all the seven elbows tested. An average curve was drawn by judgment. Points for discharges above 0.1 c.f.s. (corresponding velocity 3 ft/sec.) seem to follow a regular curve of equation:

$$Q = 0.21\ H^{.5}$$

But below this limit, the slope of the curve seems to increase and another straight line of equation:

$$Q = 0.21\ H^{.53}$$

represents the relation better. In case there is no experimental error involved, this indicates that below this average velocity the differential pressure is not proportional to the square of velocity, but to a power of less than 2.

Considering the two sections differently, points for all the elbows lie within a regular band of about ten percent deviation from the curve. If only one curve of the higher velocities is taken to hold good throughout, the maximum deviation at lower velocities goes up to 20 percent. This shows the limitations in accuracy for using any of these seven elbows uncalibrated in a normal location.

In figures 3 to 9 are drawn the individual curves for all the elbows. The constants "C" and "n" for each are as follows:

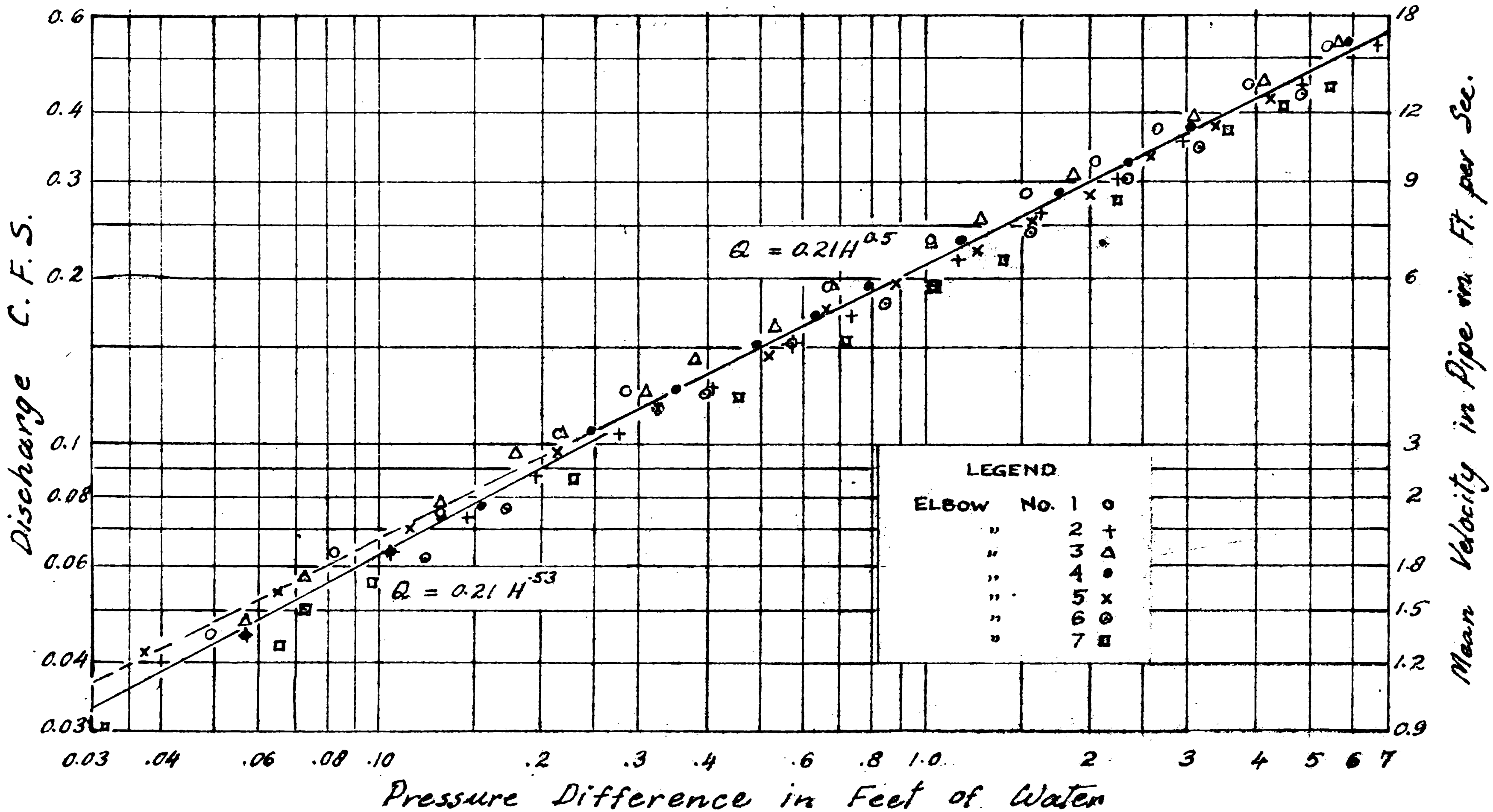


Figure 3A Pressure Discharge Relation for All Elbows

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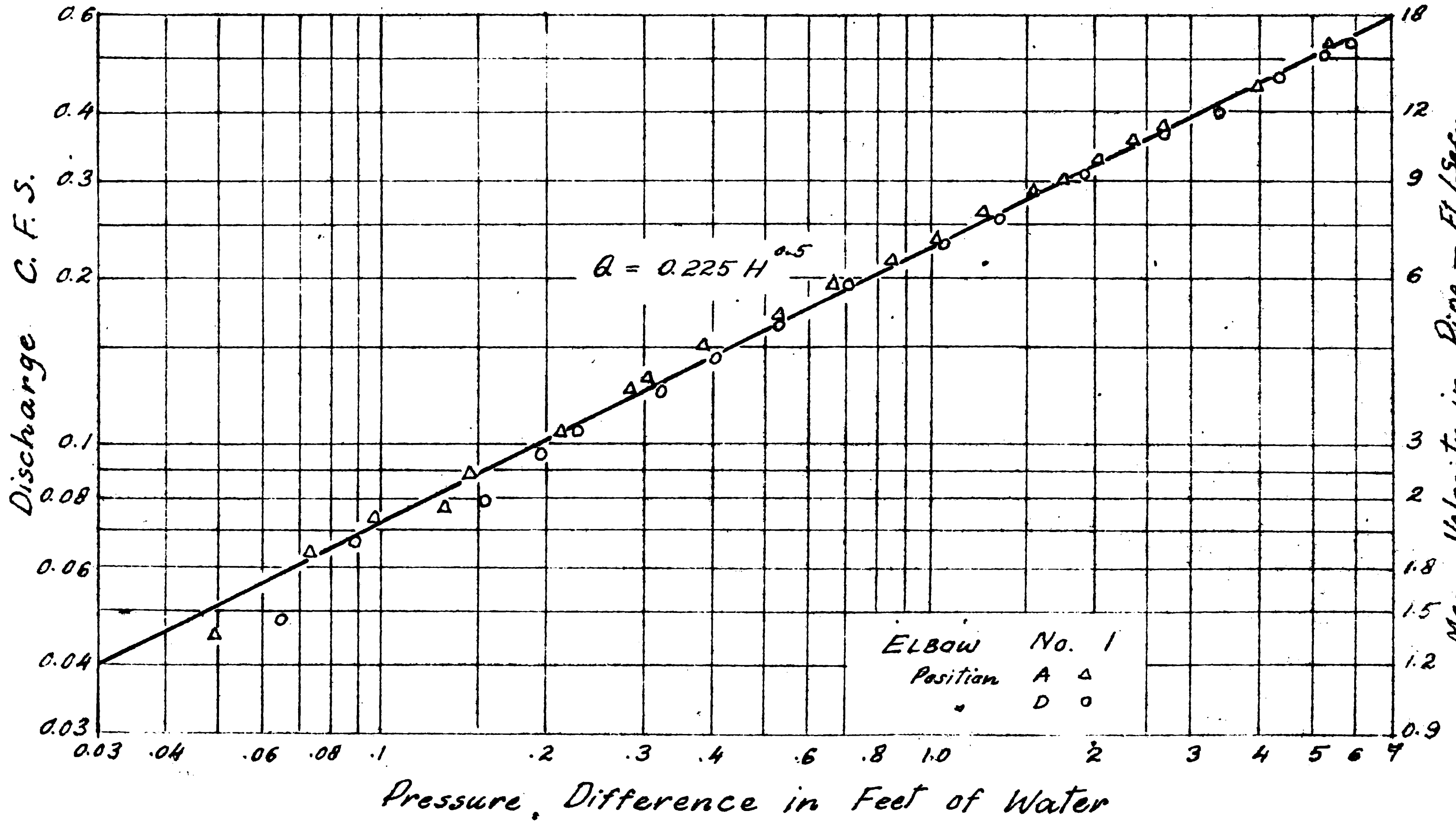

Figure 3 - Pressure Discharge Relation for Elbow No. 1

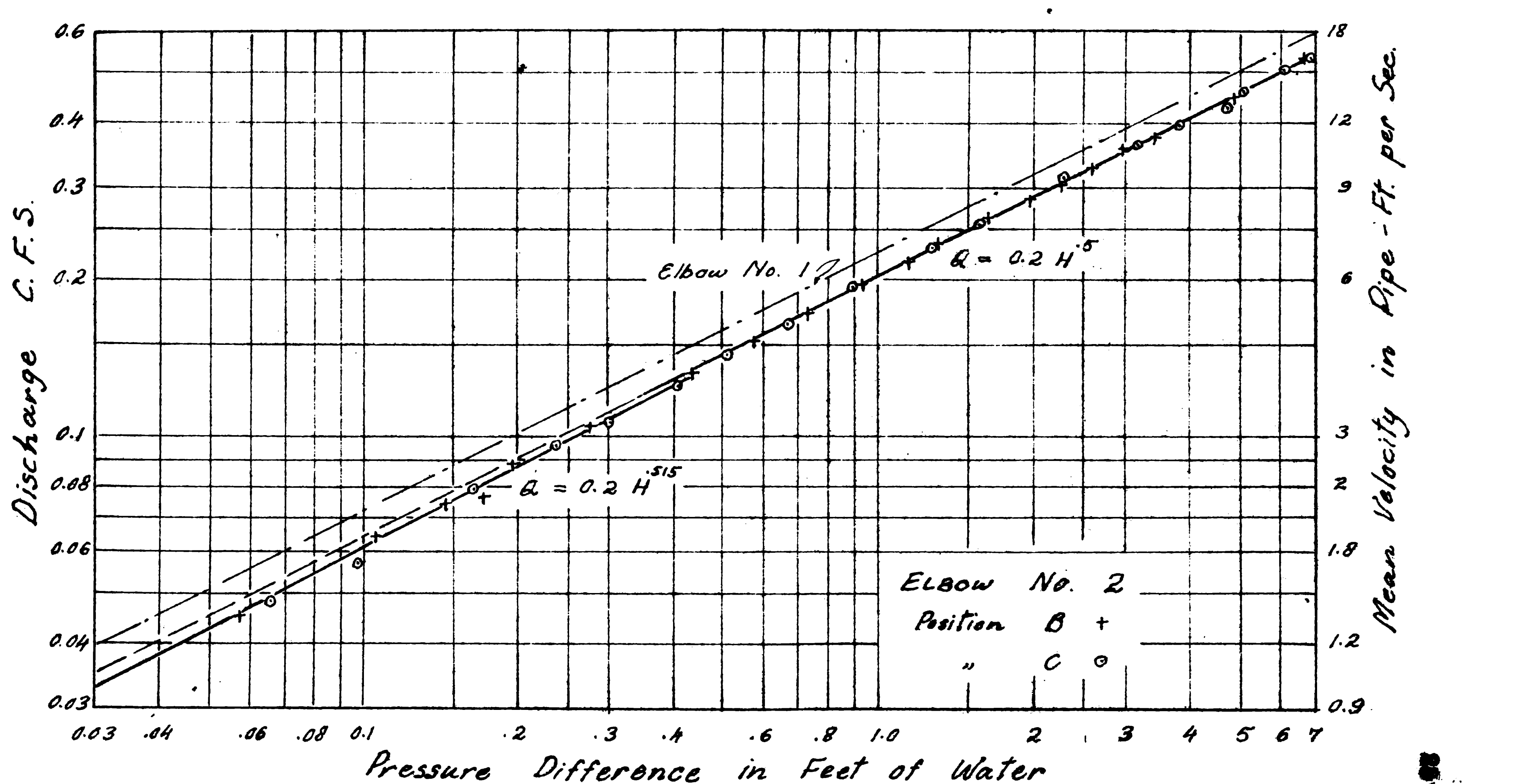

Figure 4 - Pressure Discharge Relation for Elbow No. 2

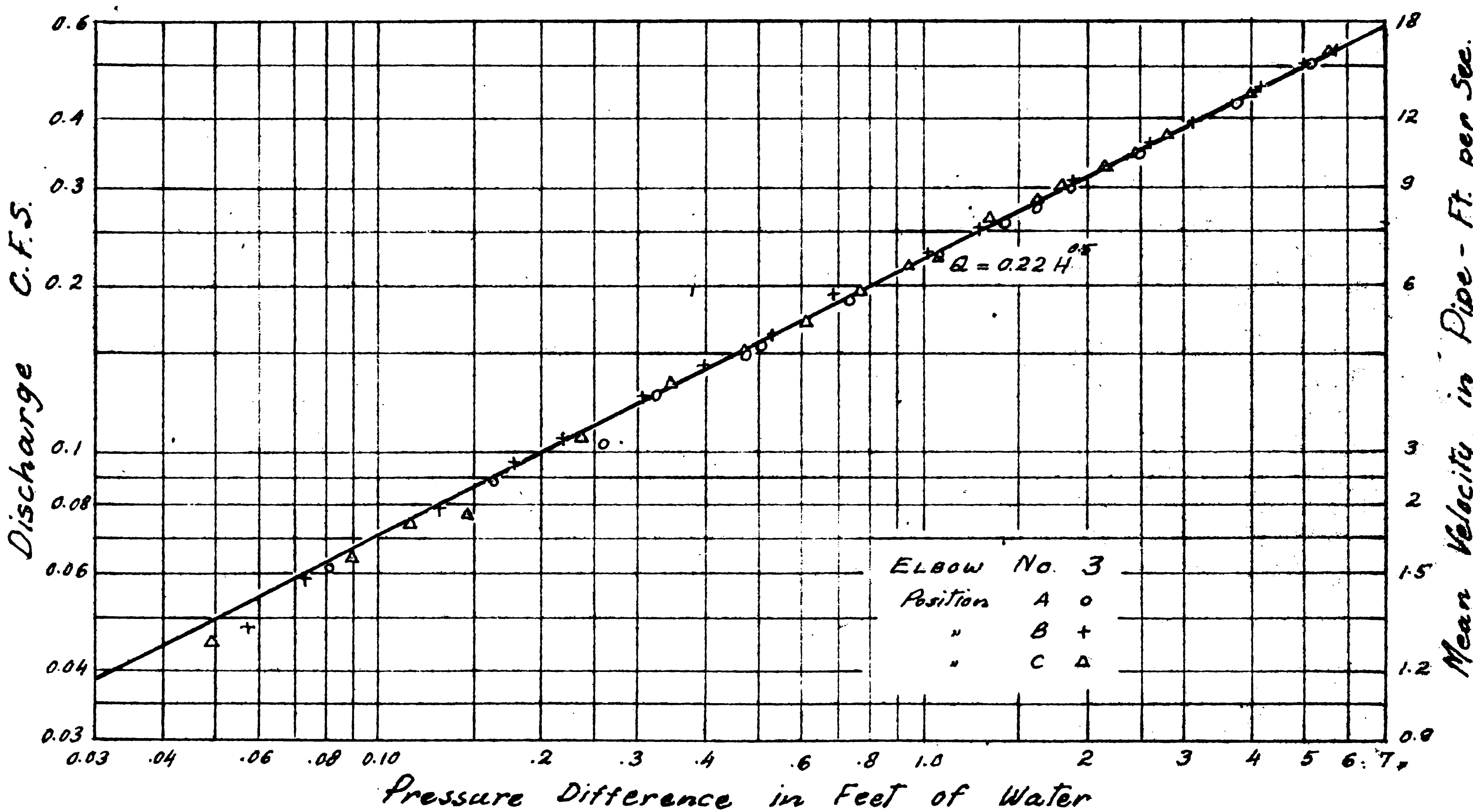

Figure 5 - Pressure Discharge Relation for Elbow No. 3

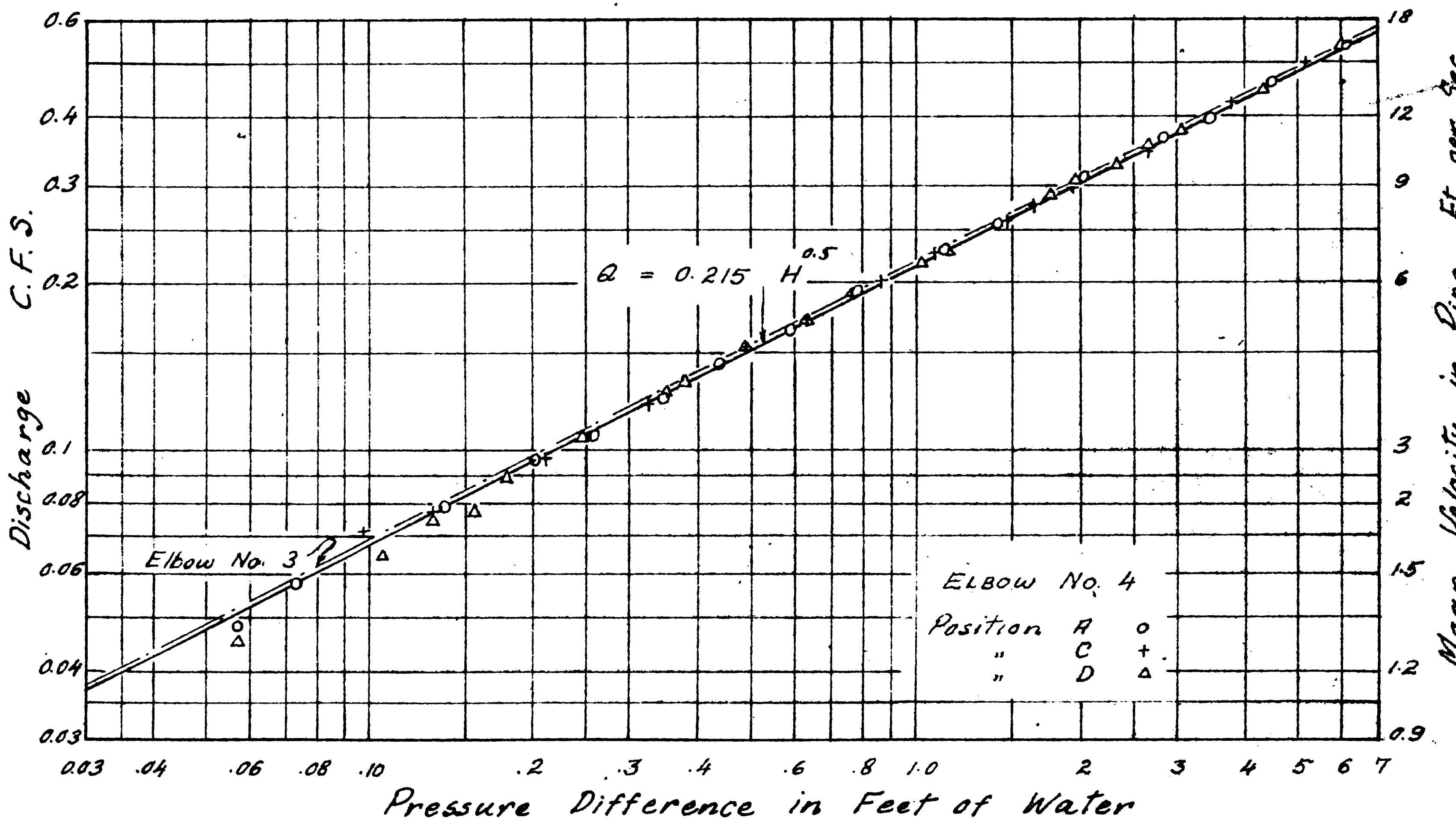

Figure 6 - Pressure Discharge Relation for Elbow No. 4

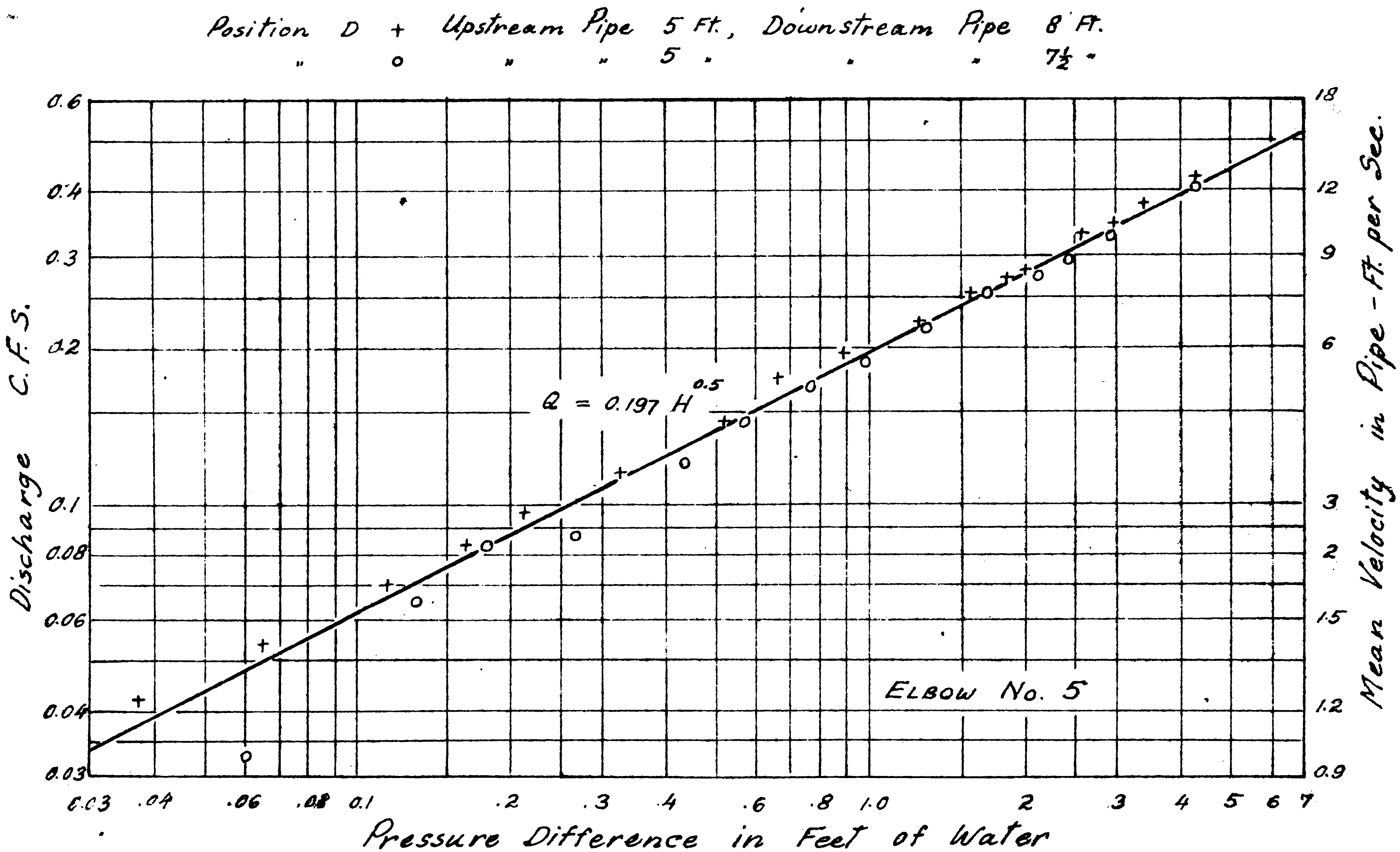

Figure 7 - Pressure Discharge Relation for Elbow No. 5

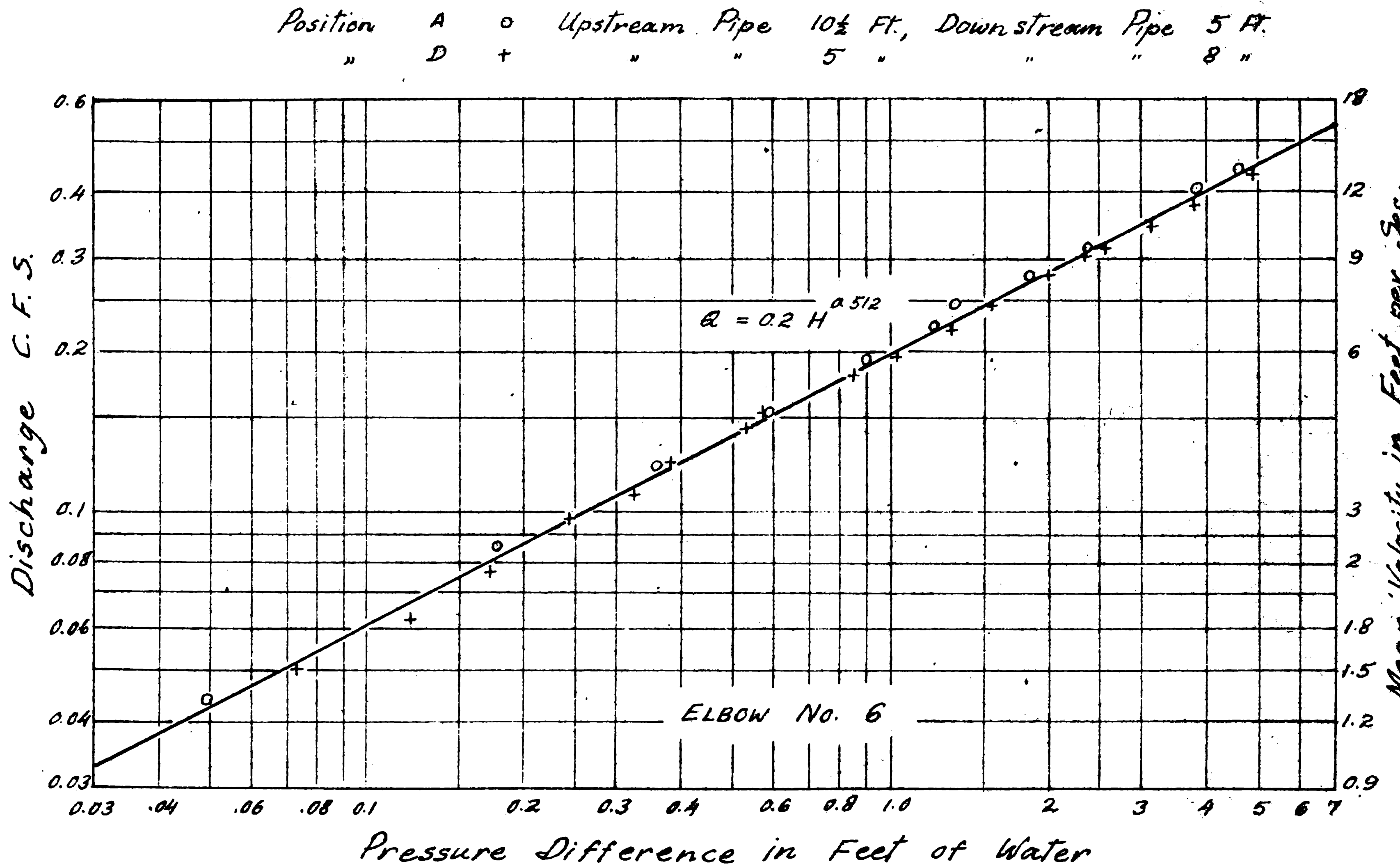

Figure 8 - Pressure Discharge Relation for Elbow No. 6

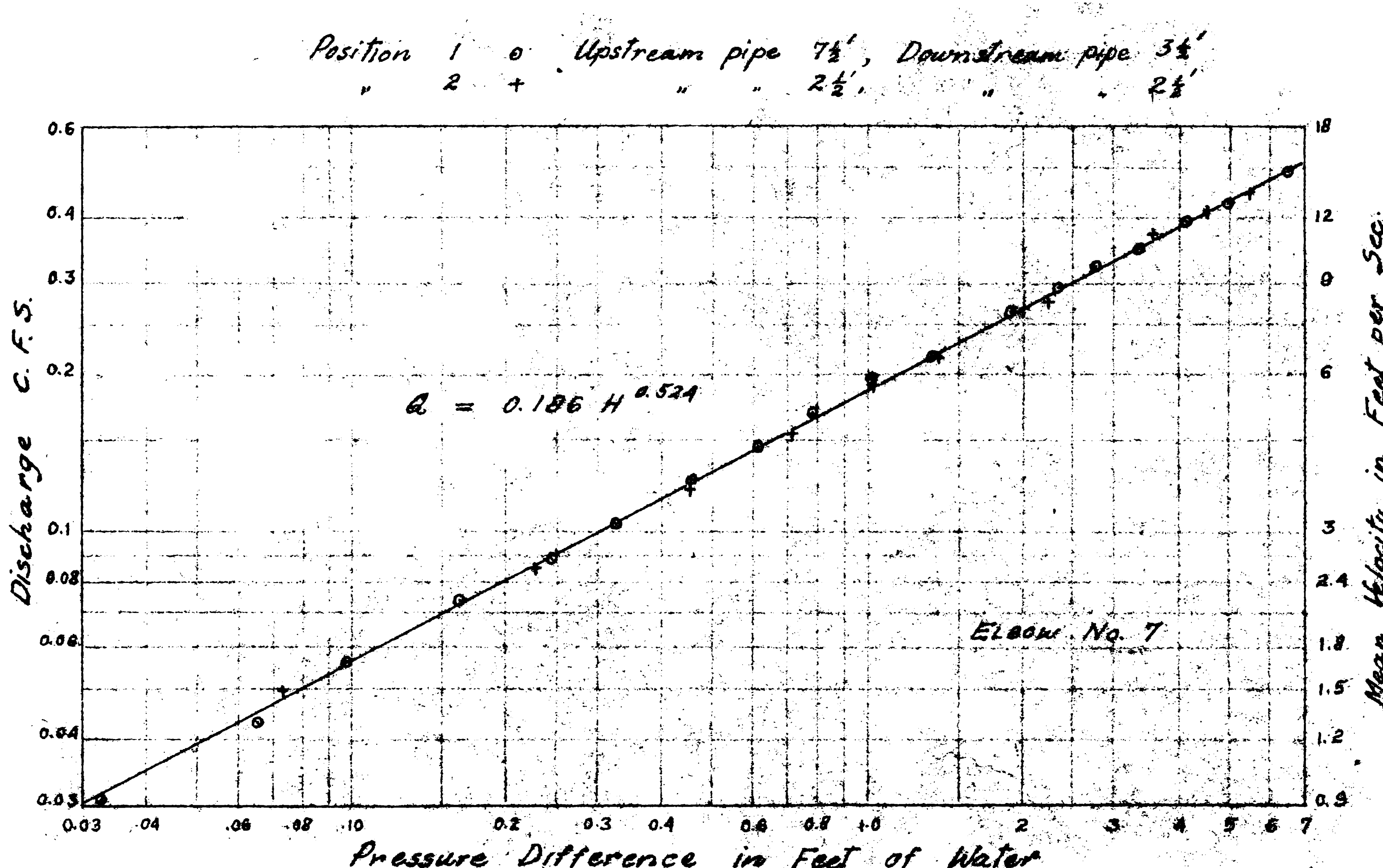

Figure 9 - Pressure Discharge Relation for Elbow No. 7

Elbow No.	C	n
1	0.225	0.500
2	0.200	0.500
3	0.220	0.500
4	0.215	0.500
5	0.197	0.500
6	0.200	0.512
7	0.186	0.524

Elbows 1 and 2 were expected to be similar in behavior, but as figures 3 and 4 will show they are not. The reason may probably be attributed to some roughness caused on the inside of elbow No. 1 during the welding of nipple on to it. This also accounts for the very irregular points on its curve in both the locations. Two separate curves, with slightly different values of "C", could be drawn for the two locations of this elbow, but in view of the irregularity of points this was not done. In figure 4 for elbow No. 2, a broken line for elbow 1 has been drawn for comparison.

Elbow No. 2 is quite consistent in its readings for both its locations. It does not give a change of constants with the change of location, but exhibits the change of slope in curve for velocities below about 4 feet per second.

As will be seen on figure 6, elbows 3 and 4 agree much more closely. The manometer with No. 3 was usually found to be more steady compared to that with No. 4. This may have been due to the two different types of pressure connections on the elbows. No. 3 had a welded nipple with 1-8-inch hole through it, while No. 4 had a screwed nipple with 3/8-inch pressure opening in its sides. The larger pressure holes in No. 4 made it more sensitive to pressure changes inside the elbow, and this caused the fluctuations in gauge columns.

Elbows 5 and 6 (figures 7 and 8) were more or less similar in behavior to Nos. 1 and 2. They actually resembled Nos. 1 and 2 in shape except that they were not galvanized. With different locations, both No. 5 and No. 6 give a slight change in the value of the constant "C", but "n", which is different for the two, remains constant. Points are rather scattered with these as compared to those of Nos. 2, 3, and 4. Of all the four elbows (1, 2, 5, and 6) of this kind tested, only No. 2 gave points closely following a straight line. It seems that this type is not so well suited for metering purposes as those of the type of No. 3 and 4.

Elbow No. 7 was the only one with Victaulic connections tested. It possessed the advantage of being easy to fit and to dismantle, and compared to all the rest of elbows it was very steady in gauge readings. As will be seen in figure 9, its points closely follow the same curve, for both its locations, down to the velocity of about one foot per second. Its steadiness was probably due to the better joints with pipe and longer radii of the inside and outside curves. For the same relative radius, with smaller thickness of metal and smaller inner diameter, it provided a more smooth inner transition than the other elbows of thicker metal.

In the case of all elbows it was noticed that when the tubes connecting the elbow to the manometer were longer than about five feet, the pressure readings were comparatively more steady.

As will be seen from figures 3 to 9, a difference of location of an elbow among the positions tried did not make any difference in the constants for that elbow. Hence, realising that flanged connections can provide a greater similarity of joints in two different locations than a threaded connection, it can be expected that an elbow calibrated at one site of a normal position can, without much error, be used uncalibrated at another normal site.

In figure 9, for elbow No. 7, are plotted points for two locations. In the first position it was preceded by 7-1/2 feet (31 d) of straight pipe, and in the second by only 2-1/2 feet (12 d). The curve indicates, however, that the difference of pipe lengths preceding the elbow did not make any marked or regular change in the working of the elbow.

CONCLUSIONS

Uncalibrated pipe elbows can be used as flow meters with greater accuracy than has so far been believed. It only requires a careful study of the various factors affecting its working to make an elbow give more precise results.

1. In one nominal size, when a set of elbows of any one particular type has been tested to establish the general equation for that type, any uncalibrated elbow of that size and type can be used to give discharges correct within 2 percent above a velocity of 3 feet per second, and correct up to 5 percent for velocities below this.

2. If elbows of one size but of different types are used, the results will be correct within 10 percent.

3. In threaded pipes, short radius elbows (of types 1, 2, 4, and 5) in which there is only a small curved space between the ends of pipes do not make consistent or steady meters.

4. Elbows with larger intervening space between pipe ends (such as Nos. 3 and 4) make more consistent and reliable meters. Among commercial elbows, medium radius and long radius elbows will be comparatively more steady in pressure readings than the short radius elbows.

5. In general, elbows with flanged or victaulic connections would give better results as meters than threaded ones.

6. A welded nipple pressure connection with 1/8-inch hole through it gives more steady gauge columns than one with tapped connection. Longer tubes between the meter and the manometer are also conducive to steadiness.

7. Difference of location of a threaded meter which otherwise gave regular points does not make any difference in the value of "n". There was a slight change in the value of "C" in some cases. It did not vary for four elbows out of seven in these experiments.

8. The presence of an elbow at 12 d upstream from one meter did not affect the value of its constants. An elbow meter can be located anywhere in a pipe line if means of calibration in service location are available.

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APPENDIX

THE USE OF ELBOWS AS FLOW METERS

Elbows 4, 3, 2, and 1 in positions
A, B. C, and D respectively

		Observed					Calculated			
		Pressure Difference in inches of liquid					Pressure Difference in feet of water			
Weight	Time	Elbow Nos.				Dis-charge	Elbow Nos.			
Lbs.	Sec.	1	2	3	4	C.f.s.	1	2	3	4
3000	89.5	36.3	41.9	34.6	37.3	.537	5.90	6.81	5.62	6.06
"	95.5	32.2	37.4	30.6	33.4	.504	5.23	6.08	4.97	5.43
"	104.5	26.7	30.9	25.4	27.5	.460	4.34	5.02	4.13	4.47
"	114.0	25.4	29.4	24.2	26.4	.421	4.13	4.78	3.93	4.29
"	121.1	20.4	23.4	19.1	21.1	.397	3.32	3.80	3.10	3.43
"	132.2	16.5	19.5	16.0	17.3	.364	2.68	3.17	2.60	2.81
"	155.0	11.8	14.0	11.5	12.4	.310	1.92	2.28	1.87	2.02
2000	125.0	8.2	9.7	7.8	8.6	.256	1.33	1.57	1.27	1.40
"	139.0	6.5	7.9	6.3	6.9	.230	1.06	1.28	1.02	1.12
"	164.9	4.4	5.5	4.2	4.7	.194	0.715	0.893	0.682	0.764
"	195.3	3.3	4.1	3.3	3.6	.164	.536	.666	.528	.585
1000	111.7	2.5	3.1	2.5	2.7	.143	.406	.504	.398	.439
"	128.0	2.0	2.5	1.9	2.15	.125	.325	.406	.309	.349
600	90.5	1.40	1.85	1.35	1.60	.106	.228	.300	.219	.260
"	100.0	1.20	1.45	1.10	1.25	.096	.195	.236	.179	.203
400	81.2	0.95	1.00	0.80	0.85	.079	.154	.162	.130	.138
300	84.0	0.55	0.60	0.45	0.45	.057	.089	.097	.073	.073
"	99.0	0.40	0.40	0.35	0.35	.048	.065	.065	.057	.057
200	115.2	0.20	.175	.10	.15	.028	.033	.028	.016	.024

THE USE OF ELBOWS AS FLOW METERS

Elbows 1, 2, 3, and 4 in positions
A, B, C, and D respectively
Manometer liquid: Acetylene tetrabromide, specific gravity 2.95

Weight Lbs.	Time Sec.	Observed Pressure Difference in inches of liquid Elbow Nos. 1	2	3	4	Discharge C.f.s.	Calculated Pressure Difference in feet of water Elbow Nos. 1	2	3	4
2000	60.0	32.8	41.1	33.8	36.5	.534	5.34	6.68	5.49	5.93
"	71.8	24.0	29.6	24.5	26.4	.446	3.90	4.01	3.98	4.29
"	84.7	16.4	21.1	17.2	18.6	.378	2.66	3.43	2.80	3.02
"	90.0	14.3	18.3	14.9	16.1	.356	2.32	2.98	2.42	2.62
"	97.2	12.5	16.0	13.2	14.2	.329	2.03	2.60	2.14	2.31
1000	53.2	10.7	13.8	11.1	12.0	.302	1.74	2.24	1.80	1.95
"	55.7	9.4	12.2	9.9	10.7	.288	1.53	1.98	1.61	1.75
"	61.0	7.7	10.0	8.1	8.9	.263	1.25	1.63	1.32	1.45
"	67.9	6.3	8.0	6.6	7.1	.236	1.02	1.30	1.07	1.15
"	73.5	5.2	7.1	5.8	6.2	.218	0.845	1.15	0.940	1.01
"	82.0	4.1	5.7	4.7	4.9	.196	0.665	0.925	0.765	0.795
"	93.7	3.3	4.5	3.7	3.9	.171	.536	.731	.601	.634
600	63.4	2.45	3.50	2.90	3.0	.152	.398	.569	.471	.487
"	73.0	1.85	2.70	2.10	2.3	.132	.301	.439	.342	.374
"	75.7	1.75	2.50	2.00	2.15	.127	.284	.406	.325	.350
400	61.0	1.30	1.70	1.45	1.50	.105	.211	.276	.236	.244
"	72.0	0.90	1.20	1.00	1.10	.089	.146	.195	.162	.179
"	82.8	0.80	1.05	0.90	0.95	.077	.130	.171	.146	.154
"	86.6	.60	.90	.70	.80	.074	.097	.146	.114	.130
300	74.5	.45	.65	.55	.65	.064	.073	.106	.089	.106
200	71.5	.30	.35	.30	.35	.045	.049	.057	.049	.057

THE USE OF PIPE ELBOWS AS ELBOW METERS

Elbows 3, 2, 4, and 5 in Positions
A, B, C, and D, Respectively

Elbow No. 3 (A)					Elbow No. 4 (C)				
			Pressure Difference					Pressure Difference	
Weight Lbs.	Time Sec.	Dis-charge C.f.s.	Inches of Liquid	Feet of Water	Weight Lbs.	Time Sec.	Dis-charge C.f.s.	Inches of Liquid	Feet of Water
3000	96.3	0.500	31.4	5.10	3000	96.3	0.500	32.0	5.2
3000	113.2	0.424	23.0	3.74	3000	113.2	0.424	23.0	3.74
2000	92.0	0.348	15.4	2.50	2000	92.0	0.348	16.2	2.64
2000	107.0	0.299	11.5	1.87	2000	107.0	0.299	11.8	1.92
1000	57.7	0.278	10.05	1.63	1000	57.7	0.278	10.1	1.64
1000	61.6	0.260	8.7	1.41	1000	61.6	0.260	9.0	1.46
1000	70.7	0.227	6.6	1.07	1000	70.7	0.227	6.7	1.09
300	25.5	0.188	4.5	0.731	300	23.8	0.202	5.3	0.861
200	20.9	0.154	3.1	0.504	200	18.8	0.171	3.8	0.628
200	21.4	0.150	2.9	0.471	200	20.7	0.155	3.0	0.488
200	25.5	0.126	2.0	0.325	200	26.4	0.121	2.0	0.325
100	15.7	0.102	1.6	0.260	100	16.5	0.097	1.3	0.211
100	18.2	0.088	1.0	0.163	100	20.9	0.077	0.8	0.130
100	25.4	0.061	0.5	0.081	50	11.0	0.072	0.6	0.975

THE USE OF PIPE ELBOWS AS FLOW METERS

Elbow No. 5: Upstream Pipe - 5 feet
Downstream Pipe - 7-1/2 feet
Elbow No. 6 - Position A

Elbow No. 5					Elbow No. 6				
			Pressure Difference					Pressure Difference	
Weight Lbs.	Time Sec.	Dis-charge C.f.s.	Inches of Liquid	Feet of Water	Weight Lbs.	Time Sec.	Dis-charge C.f.s.	Inches of Liquid	Feet of Water
1000	39.4	0.407	28.8	4.35	1000	36.5	0.440	28.2	4.58
500	24.5	0.327	18.0	2.92	500	25.5	0.314	14.5	2.36
500	27.2	0.295	15.0	2.44	500	19.7	0.406	23.5	3.82
500	29.0	0.276	13.0	2.11	500	28.7	0.279	11.2	1.82
300	19.0	0.253	10.4	1.69	500	32.4	0.248	8.10	1.32
300	22.0	0.218	7.8	1.27	300	21.6	0.223	7.4	1.20
300	26.0	0.185	6.0	0.975	200	16.5	0.195	5.5	0.894
200	18.9	0.169	4.7	0.765	200	20.8	0.154	3.6	0.585
200	22.2	0.144	3.5	0.569	200	26.4	0.121	2.25	0.366
200	26.7	0.120	2.55	0.415	100	18.5	0.086	1.10	0.179
200	37.2	0.086	1.70	0.276	100	36.5	0.044	0.30	0.049
100	19.3	0.083	1.10	0.179					
100	24.5	0.065	0.80	0.130					
50	24.0	0.033	0.37	0.060	Elbow No. 2 - Position B				
					1000	41.2	0.395	22.9	3.72
					500	24.0	0.334	17.5	2.84
					500	26.5	0.303	13.6	2.21
					500	29.5	0.272	10.7	1.74
					400	30.7	0.209	6.6	1.07
					400	37.9	0.175	4.5	0.731
					300	36.0	0.133	2.95	0.48
					150	24.5	0.098	1.50	0.244
					100	25.2	0.064	0.55	0.0894
					50	17.1	0.047	0.45	0.073

Elbow Nos. 5 and 6 Position D

Both: Upstream - 5 feet straight
Downstream - 8 feet straight

Elbow No. 5 (D)					Elbow No. 6 (D)				
			Pressure Difference					Pressure Difference	
Weight Lbs.	Time Sec.	Dis-charge C.f.s.	Inches of Liquid	Feet of Water	Weight Lbs.	Time Sec.	Dis-charge C.f.s.	Inches of Liquid	Feet of Water
2000	76.0	0.421	26.0	4.22	1000	42.0	0.379	23.3	3.79
1000	42.2	0.380	20.8	3.38	1000	37.1	0.432	29.9	4.86
1000	45.9	0.348	18.3	2.97	500	23.2	0.345	19.3	3.14
500	24.2	0.331	15.8	2.57	500	25.8	0.311	15.8	2.57
500	28.2	0.284	12.3	2.00	500	26.5	0.303	14.3	2.32
500	29.1	0.275	11.2	1.82	500	28.6	0.280	12.3	2.00
500	31.5	0.255	9.7	1.57	500	32.8	0.244	9.55	1.55
500	35.9	0.223	7.6	1.23	500	36.4	0.220	8.00	1.30
300	24.4	0.197	5.4	0.88	500	41.0	0.196	6.30	1.02
300	29.0	0.176	4.05	0.66	500	44.6	0.180	5.2	0.845
300	32.8	0.146	3.20	0.52	300	31.6	0.152	3.50	0.570
200	27.5	0.116	2.00	0.325	300	33.5	0.143	3.30	0.536
200	33.0	0.097	1.30	0.211	200	26.0	0.124	2.45	0.398
100	19.0	0.084	1.0	0.163	200	29.6	0.108	2.0	0.325
100	23.0	0.070	0.7	0.114	100	16.5	0.097	1.45	0.236
100	29.6	0.054	0.4	0.065	100	21.1	0.076	1.05	0.171
100	38.5	0.042	0.23	0.037	100	25.7	0.062	0.75	0.122
					100	31.9	0.050	0.45	0.073
					50	28.3	0.028	0.15	0.024

THE USE OF PIPE ELBOWS AS FLOW METERS

Elbow No. 7 (Victaulic)

Position 1: Upstream Pipe 7-1/2 ft.
Downstream Pipe 3-1/2 feet

Position 2: Upstream Pipe - 2-1/2 ft.
Downstream Pipe - 2-1/2 ft.

Position 1					Position 2				
			Pressure Difference					Pressure Difference	
Weight Lbs.	Time Sec.	Dis-charge C.f.s.	Inches of Liquid	Feet of Water	Weight Lbs.	Time Sec.	Dis-charge C.f.s.	Inches of Liquid	Feet of Water
3000	98.5	0.488	40.10	6.51	1000	36.0	0.446	33.6	5.45
1000	37.8	0.424	30.60	4.98	1000	39.5	0.412	27.7	4.50
1000	41.0	0.391	25.3	4.11	1000	43.0	0.373	22.0	3.58
500	23.0	0.348	20.4	3.32	500	28.9	0.278	13.8	2.24
500	24.8	0.323	17.0	2.76	200	14.7	0.218	8.5	1.38
500	27.3	0.294	14.4	2.34	300	25.2	0.191	6.2	1.01
500	30.5	0.263	11.65	1.89	200	20.9	0.154	4.4	0.715
500	36.8	0.218	8.10	1.32	200	25.5	0.121	2.8	0.455
500	41.0	0.196	6.20	1.01	200	37.1	0.086	1.4	0.228
300	28.2	0.170	4.80	0.780	100	32.2	0.050	0.45	0.073
300	33.0	0.146	3.80	0.618					
200	25.5	0.125	2.80	0.455					
200	28.7	0.102	2.0	0.325					
200	36.2	0.089	1.50	0.244					
100	21.6	0.074	1.00	0.163					
100	28.5	0.056	0.60	0.0975					
100	37.4	0.043	0.40	0.065					
50	26.0	0.031	0.20	0.0325					